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Quantitative decision making in animal health surveillance: Bovine Tuberculosis Surveillance in Belgium as case study

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Abstract

Despite eradication and control measures applied across Europe, bovine tuberculosis (bTB) remains a constant threat. In Belgium, after several years of official bTB-free status, routine movement testing, as currently practiced, revealed itself inadequate to detect some herds affected by sporadic breakdowns. The aim of this study was to assess different surveillance system components that strike a balance between cost and effectiveness and to identify sustainable alternatives, which substantiate a bTB-free claim while ensuring early detection and acceptance by various animal health stakeholders. For this pupose, a stochastic iteration model was used to simulate the current surveillance system's expected performance in terms of detection sensitivity and specificity. These results were then descriptively compared with observed field results. Second, the cost and effectiveness of simulated alternative surveillance components were quantified. Sensitivity analyses were performed to measure key assumptions' impacts (i.e. regarding diagnostic tests and true prevalence). The results confirmed discrepancies between the observed and simulated expected performance of bTB surveillance in Belgium. Second, simulated alternatives showed that interferon gamma (IFN-γ) and serological testing with antibody-enzyme linked immunosorbent assay (Ab-ELISA) targeting at-risk herds would enable an increase in the overall cost effectiveness (sensitivity and specificity) of the Belgian bTB surveillance system. Sensitivity analyses showed that results remained constant despite the modification of some key assumptions. While the performance of the ongoing bTB surveillance system in Belgium was questionable at the time of the study, this exercise highlighted that not only sensitivity but specificity also are key drivers of surveillance performance. The quantitative approach, taking into consideration various stakeholders' needs and priorities, revealed itself to be a useful tool in allowing evidence-based decision making for future tuberculosis surveillance in Belgium, in line with the international standards.

KEYWORDS
Bovine Tuberculosis, Cost-effectiveness, Modelling, Surveillance

Abbreviations: Ab-ELISA, antibody-enzyme linked immunosorbent assay; bTB, bovine tuberculosis; CSe, component sensitivity; $Cost_{Si}$, cost of each simulated scenario; $Cost_{Test}$, cost of the diagnostic test; $Cost_{VetVisit}$, cost of the veterinary visit; EU, European Union; FASFC, Federal Agency for the Safety of the Food Chain; FC, fattening calves; FN, false negative; FP, false positive; ID, identification; IFN-γ, interferon gamma; IMP, importation; MS, Member States; n_{Cattle}, number of cattle tested; $n_{CattleinHerd}$, number of cattle within herds tested; $n_{HerdsVisited}$, number of herds visited; n_{Herd}, number of herds tested; $N_{CattleinHerd}$, number of cattle within a herd present; N_{Herd}, number of herds present; P, prevalence; PA, prevalence within herd level; PH, prevalence at herd level; PUR, purchase; SANITEL, Belgian national registration systems of animal identification and movement; Se, sensitivity; Se_{Herd}, herd sensitivity; Se_{Test}, sensitivity of test within herd; SICT, single intradermal comparative test; SIT, single intradermal tuberculin test; SLGH, slaughterhouse; Sp, specificity; TN, true negative; TP, true positive; WS, winter screening

1 | INTRODUCTION

Bovine tuberculosis (bTB) is caused by *Mycobacterium bovis*, which affects humans, cattle and other domesticated animals as well as wildlife species. Despite efforts made over the last decades to eradicate the disease, bTB is still (re-)emerging in some European Union (EU) Member States (MS) and worldwide (EFSA, 2018; Quadri et al., 2021; Visavet, 2019). The specific characteristics and complex epidemiology of the etiological agent together with limitations of current diagnostic assays and the lack of disease awareness (i.e. after several bTB-free years) make surveillance and control of bTB constant and evolving challenges (Downs, Parry, et al, 2018; Downs, More, et al., 2018; Humblet et al., 2009; King et al., 2015; Shiller et al., 2010, 2011). In addition, bTB control accounts for a large share of Belgium's animal health expenditures, which requires the search for a cost-effective and sustainable surveillance programme (Drewe et al., 2014).

Following a successful eradication campaign and the constant decrease in the total number of bTB-cases since the end of the 1990s, Belgium was officially declared bTB-free in 2003 (EC, 2003). From that time, the status of the cattle population was maintained as bTB-free, with annual herd prevalence below 0.1%, corresponding to minimum European legal requirements (EC, 1964, 2003).

Several studies assessing Belgian national registration systems of animal identification and movement (SANITEL), coupled to historical surveillance data, have revealed that the main risk factors for bTB sporadic breakdown herds in Belgium were a previous bTB infection and animal movements, as indicated by observations made elsewhere in the world (Conlan et al., 2012; Humblet et al., 2010; Guta et al., 2014; More et al., 2015; Palisson et al., 2016). However, over the last decade in Belgium, mandatory testing of newly introduced cattle (i.e. following purchase) did not detect infected cattle. Nonetheless, when sporadic breakdown herds are only detected at later stages of infection (e.g. at slaughter houses), assessment of earlier data and additional tracing have highlighted probable discrepancies in test results (Calba et al., 2016; Humblet et al., 2010, Humblet, Walravens, et al., 2011; Humblet, Moyen, et al., 2011; Welby et al., 2012). In addition, the within-herd high prevalence of reactor cattle detected at times in breakdown, combined with the chronic stage of infection in infected cattle (generalised lesions found on slaughtered animals) raised serious doubts about the current 'early warning' aspect of testing at purchase and/or slaughter house visual inspection (FASFC, 2020).

While there is a clear need for sustainable cost and effective surveillance systems to detect (re-) emerging diseases to ensure public health, safe animal trade and welfare, criteria and tools to evaluate these systems and to foster mutual trust among stakeholders are still lacking (Calba et al., 2015, 2016; Drewe et al., 2012; Stärk & Häsler, 2015). Following a request from the Belgian scientific food safety committee (FASFC, 2016), a task force, comprising different animal health stakeholders (farmers, veterinarians, agricultural food sector, regional and central laboratories, animal health control and policy makers, relevant authorities and paymasters) was set to evaluate the performance of the current surveillance system and explore possible surveillance alternatives. Thus, the current study, mandated by the task force, intended to allow for evidence-based decision in the future bTB surveillance system to substantiate free-status claim and to detect cases early on. For this purpose, a stochastic simulation model was developed to evaluate the performance of surveillance components in terms of cost and effectiveness.

2 | MATERIALS AND METHODS

2.1 | Input data

At the time of the current study, the surveillance of cattle in Belgium was implemented and coordinated at the national level by the Federal Agency for the Safety of the Food Chain (FASFC) in accordance with the guidelines laid down in Council Directive 64/432/EEC and in the Royal Decree 17.10.2002 (EC, 1964; Moniteur Belge, 2003). The four on-going surveillance components of bTB surveillance system in Belgium were as follows (Figure 1):

(i) Slaughterhouse (SLGH): It includes post-mortem inspection at slaughterhouses of all slaughtered cattle.
The three other components, using a single intradermal tuberculin test (SIT) as first-line screening were as follows:
(ii) Importation (IMP): It means testing of all imported cattle from non-officially and officially bTB-free MS at the import stage. This excludes young fattening calves (FC), which are sent to slaughterhouse at the age of 6 months.
(iii) Purchase (PUR): It includes testing of all purchased cattle (national trade), except for FC.
(iv) Winter screening (WS):
   a. Testing during five consecutive years of all cattle older than 6 months from herds identified during tracing-on and tracing-back investigation as linked to an outbreak.
   b. Testing during three consecutive years for all imported cattle from non-officially bTB-free MS.
   c. Testing of all females older than 24 months belonging to farms with direct 'raw milk-sales' to consumers.

A single intradermal comparative test (SICT) was performed 6 weeks after each non-negative SIT and the reactor cattle was isolated from the rest of the herd. In case of non-negative SICT result, the reactor animal is slaughtered and the whole herd is under movement restriction. Suspected gross lesions (identified by inspection, palpation, incision of organs and tissues) and selected lymph nodes from the slaughtered cattle were sent to the National Reference Laboratory for tuberculosis culture and identification. If these tissues were also confirmed bTB-positive at the laboratory, the whole herd was screened with an SIT test and all reactor animals were slaughtered. Depending on epidemiological investigation, the whole herd could be slaughtered. Once bTB was detected in a herd, a thorough tracing-on and tracing-back investigation of all contact animals and herds would be carried out

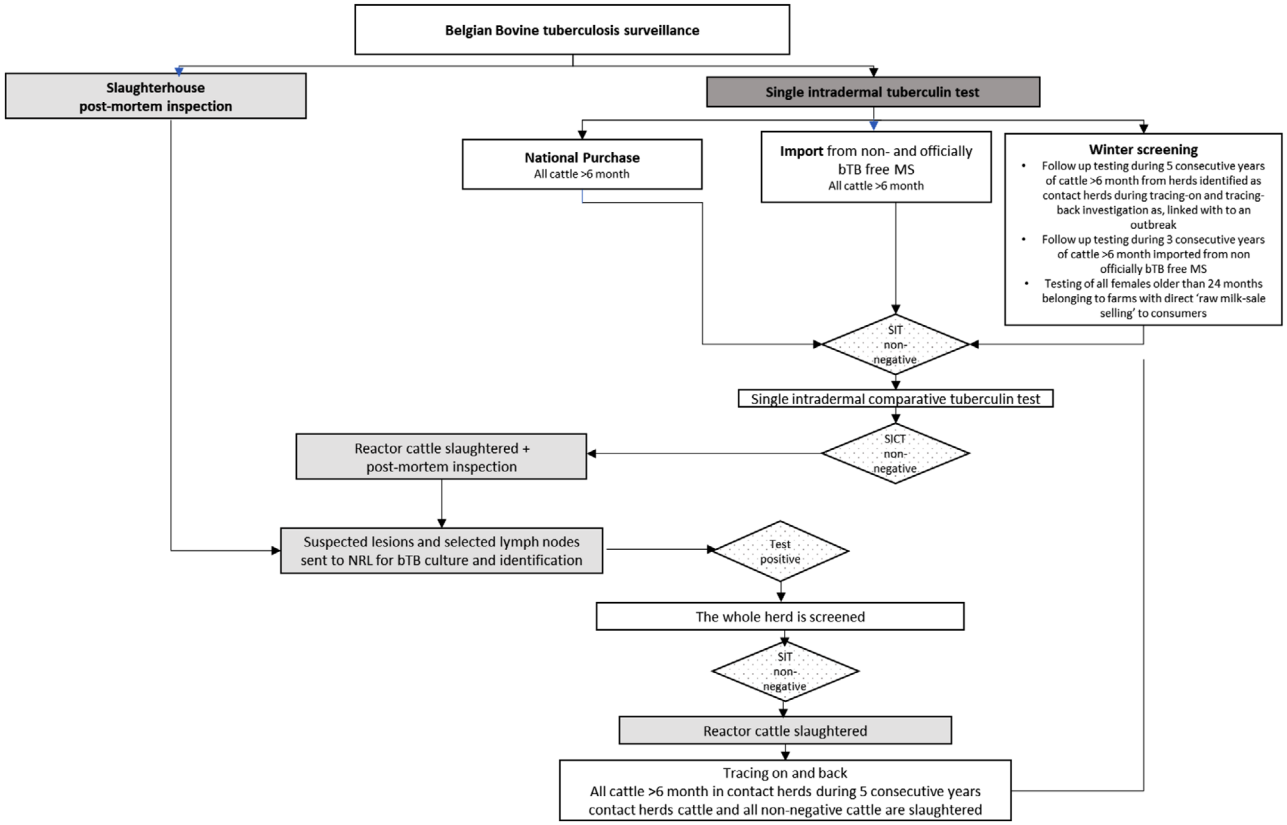

FIGURE 1 The main components of bTB surveillance in Belgium.
Abbreviations: MS, Member State; NRL: national reference national laboratory; SIT, single intradermal test; SICT, single intradermal comparative test; bTB: bovine tuberculosis

and those contact herds would be tested for five consecutive years by SIT in WS.

Since it is critical for early detection to rapidly and effectively identify potential infection before it spreads, it was suggested to increase detection sensitivity in cattle and herds identified by tracing on and back and/or imported from non-officially bTB-free MS. It was assumed that to increase detection sensitivity, not only should the diagnostic test characteristics be more sensitive but also they should be more reliable in results interpretation without compliance issues. Hence, antibody-enzyme linked immunosorbent assay (Ab-ELISA) and interferon gamma (IFN-γ) were identified as interesting alternatives, in contrast to SIT that requires a second on-farm visit and more subjective nature of result interpretation. To estimate yearly potential impact (in terms of detection sensitivity but also false and true positives and negative results) of these alternative testing schemes targeting cattle herds identified after tracing-on and -back of bTB breakdown(s) and/or having an introduction of cattle originating from a non-officially bTB-free MS, additional scenarios were simulated. The different simulated scenarios were for comparing the different testing schemes: interferon SIT, (IFN-γ) test, Ab-ELISA alone or alongside IFN-γ.

To feed the simulation models (further description hereafter), yearly data regarding all on-farm cattle censuses and movements from 1 January 2010 to 31 December 2015 (births, slaughters, purchases and imports) were collected from SANITEL. For each individual cattle and herd, the following variables were compiled: cattle identification (ID), herd of origin ID, herd of destination ID, birth date, movement date, movement type (birth, purchase, import, export, slaughter, rendering plant and market), cattle type 1 (fattening calves vs. others), cattle type 2 (mixed, meat and dairy). Data were merged and concatenated at surveillance component level to get the annual population and tested numbers of cattle and herds tested in each surveillance component. Data management and analysis was carried out in SAS 9.2.

Annual on-going surveillance data were obtained from the FASFC and regional laboratories in Belgium (named DGZ and ARSIA) for the years 2010–2015. Data regarding costs of surveillance procedures were obtained from the FASFC and the Sanitary Funds for cattle industry for the years 2010–2015.

The simulated herd level design prevalence was set as that of the official herd level design bTB prevalence (0.1% as indicated in Directive 64/432/CEE (EC, 2003). Due to the absence of exact information on within herd prevalence, an arbitrary prevalence of 0.01% at animal level and 10% level within herd (as seen in breakdown herds in Belgium over last decade) was simulated. The same prevalence across all components was simulated, as this would represent the worst-case scenario. If the relative risk of infection was higher in the IMP component, the sensitivity of detection would also increase. In addition, given the

TABLE 1 Model parameters and assumptions values and sources

Parameter definition	Value[a]	Sources
Average yearly cattle herd population size	24,000(22,000–25,000)	National animal identification and movement registration system, Federal Agency Food Safety Chain, Sanitary Fund
Average yearly cattle population size	2,500,000(2,200,000–2,700,000)	
Average yearly herd size	53(8–143)	
Average yearly number of purchased cattle	345,298(338,392–352,066)	
Average yearly number of slaughtered cattle	501,189 (491,165–511,012)	
Average yearly number of tracing outbreak cattle tested during winter screening	216,643(212,310–220,889)	
Average yearly number of tracing import and dairy tested cattle during winter screening	81,653(80,021–83,253)	
Simulated number of herds in alternative component	215	
Simulated number of cattle in alternative component: number of cattle	13000	
Sensitivity Ab-ELISA	0.56(0.04–0.98)	Bezos et al., 2014; Casal et al., 2017; EFSA, 2013; Garcia-Saenz et al., 2015 ; Schiller et al., 2010, 2011
Specificity Ab-ELISA	0.92(0.81–0.97)	
Sensitivity tuberculin skin test	0.94(0.49–1)	
Specificity tuberculin skin test	0.91(0.7–1)	
Sensitivity IFN-γ	0.77(0.61–0.89)	
Specificity IFN-γ	0.98(0.95–0.99)	
Sensitivity slaughterhouse inspection	0.71(0.38–0.92)	
Specificity slaughterhouse inspection	1(0.99–1)	
Cost Ab-ELISA (€)	4(3–5)	Federal Food Safety Agency, Sanitary Fund
Cost tuberculin skin test (€)	2(1–3)	
Cost IFN-γ (€)	17(15–25)	
Cost of farm visit by the vet (€)	30.13	
Animal Prevalence	0.0001	Simulated
Herd prevalence	0.0010	64/432/CEE
Within-herd prevalence	0.100	Simulated

[a]Pert probability distribution functions with most likely (minimum-maximum) values were used for some parameters reflecting uncertainty and variability around the input data estimates.

fact that cattle exported from non-officially free countries should comply with strict sanitary and additional testing requirements, it can be assumed that the likelihood of infection is similar for those cattle then those of the importing country.

The diagnostic test characteristics (sensitivity and specificity) of the SIT at purchase and visual slaughterhouse post-mortem inspection, as well as alternative diagnostic methods were obtained from targeted literature reviews with data lock point of September 2017 (Bezos et al., 2014; Casal et al., 2017; EFSA,2013; Garcia-Saenz et al., 2015; Schiller et al., 2010, 2011).

Table 1 displays the different input parameters and assumptions, together with respective values and sources. Pert probability distribution functions, with most likely (minimum-maximum) estimated averaged values, were attributed to all parameters, reflecting the uncertainty and variability of source data (i.e. population and surveillance herd and cattle population, test characteristics, as well as minimum legal requirements). These inputs parameters were fed into the stochastic models—further description below.

2.2 | Model

First, the simulated expected negative and positive results in the tested cattle population given testing schemes applied in different on-going bTB surveillance components (SLGH, IMP, PUR, WS), in Belgium at the time of the study, were computed with the following equations:

$$TP = Se \times P \times n \quad (1)$$

$$TN = Sp \times (1 - P) \times n \quad (2)$$

$$FP = (1 - Sp) \times (1 - P) \times n \quad (3)$$

$$FN = (1 - Se) \times P \times n \quad (4)$$

where TP is the number of simulated expected true positive, TN is true negative, FP is false positive and FN is false negative depend on the

sensitivity (Se) and the specificity (Sp) of the tests used, the animal level prevalence (P) as well as the number of cattle tested (n).

Second, the simulated expected numbers of positive reactors (TP + FP) were used as a benchmark to compare with observed annual surveillance results data obtained from FASFC and regional animal health organisations in Belgium during the years 2010 until 2015.

Third, a simple stochastic model was built to simulate on-going and alternative surveillance components to examine and determine the most optimal scenario considering its costs and effectiveness.

The effectiveness of each simulated alternative surveillance component was estimated by its sensitivity of detection (probability of positive result in the component given that the population is infected at the specified design prevalence), as it is the sensitivity which in turn would trigger interventions in case of unfavourable results and thereby limit the spread of infection. This was computed using the following equations below, adapted from Martin et al. (2007).

$$CSe = 1 - \left(1 - Se_{Herd} \times \left(\frac{n_{Herd}}{N_{Herd}}\right)\right)^{(N_{Herd} \times PH)} \quad (5)$$

$$Se_{Herd} = 1 - \left(1 - Se_{Test} \times \left(\frac{n_{CattleinHerd}}{N_{CattleinHerd}}\right)\right)^{(N_{CattleinHerd} \times PA)} \quad (6)$$

Component sensitivity (CSe) (probability of positive result in the component given that the population is infected at the specified design prevalence) for each component (i) was estimated taking into account the number of herds present in the population (N_{Herd}), the number of herds tested (n_{Herd}), the expected prevalence at herd level (PH) and mean herd sensitivity (Se_{Herd}), in the given component. The mean Se_{Herd} estimate, for each component, was based on the average distribution of the number of cattle in a herd ($N_{CattleinHerd}$), the number of cattle tested ($n_{CattleinHerd}$), the expected prevalence at within herd level (PA) and within herd test sensitivity (Se_{Test}).

The potential risk of missing an infected animal was estimated by computing the expected total FN results at animal level for each given component (Equation 4).

The cost of each simulated alternative scenario ($Cost_{Si}$) was derived by considering the number of cattle tested ($n_{AnimalTested}$), the cost of the diagnostic test ($Cost_{Test}$) and the number of visited herds for testing ($n_{HerdsVisited}$) as well as the cost of a veterinary visit ($Cost_{VetVisit}$; times one for serological assays and IFN-γ and times two for tuberculin skin testing) (Equation 7).

$$Cost_{Si} = [n_{AnimalTested} \times Cost_{Test}] + [n_{HerdsVisited} \times Cost_{VetVisit}] \quad (7)$$

Additional costs incurred by confirmation testing (with IFN-γ and Ab-ELISA in parallel) of each true and false positive result was also considered by using the same equation (Equation 7), where $n_{AnimalTested}$ and $n_{HerdsVisited}$ represented the numbers of true and false positive reactors and herds.

The outputs generated for each simulated surveillance components were obtained by a stochastic iteration process in @Risk 5.0, with 10,000 iterations per simulation to ensure model convergence.

2.3 | Sensitivity analysis

To understand the impact of some of the assumptions used in the above modelling exercise, different sensitivity analyses were carried out.

It was argued that the apparent prevalence of bTB in Belgium may be underestimated because of current diagnostic constraints. Therefore, a sensitivity analysis was carried out to measure the impact of prevalence (1 infected in 100,000 cattle; 1 infected in 10,000; 1 infected in 1000) on the purchase testing results while keeping all other parameters unchanged.

Since serological tests target humoral immune responses (i.e. Ab-ELISA), the probability of detection will vary depending on the infection stage (acute infection or chronic infection) and prevalence, different scenarios were therefore simulated reflecting varying diagnostic Ab-ELISA test sensitivities (Casal et al., 2017), using conventional proteins, specific immune mediated proteins or with no prior knowledge of diagnostic test sensitivity values. Also, to understand the impact of prior probability distribution functions, different functions were used. The beta is a continuous probability distribution characterised by two shape parameters (α, β) and often used for random behaviour percentages and proportions such as diagnostic tests characteristics (sensitivity and specificity). Hence, simulations were carried out with Pert distribution 0.56(0.04–0.98); beta distribution (79,62) corresponding to a mean (min–max) value of 0.56 (0–1); beta distribution (11,29) corresponding to a mean (min–max) value of 0.93 (0–1); beta distribution (2,2) corresponding to a mean (min–max) value of 0.5 (0–1).

3 | RESULTS

3.1 | Model output

The simulated expected results (mean estimate, minimum and maximum) of different on-going surveillance components were compared with the annual surveillance results (Table 2). The simulated expected SIT positive reactors (TP + FP) at purchase (38,006 (224–101,042)) were more than 1000 times higher than observed (9(2–14)). While the observed SIT false positive reactors during winter screening (390(65–498)) were lying within the expected positive reactors lower range (23,846(140–63,335)), observed slaughterhouse inspection lesion notification number (16(2–86)), though not as high as expected, was lying within the simulated expected range (870(26–4684)).

Second, scenarios simulating different testing schemes were tested (Table 3). Regardless of the diagnostic test used, the number of false negative results remained constantly low (0(0–3). The simulated expected component sensitivity of each alternative testing scenario remained within the same range, regardless of their respective test sensitivity values, which means that the overall expected sensitivity of the surveillance would not drastically change given the chosen strategy and testing scheme. However, the number of false positives was much lower using IFN-γ. Similar overall costs were observed for SIT and

TABLE 2 Number of observed and simulated expected positive reactors (true + false positives) within the different bovine tuberculosis surveillance components on-going in Belgium using the single intradermal tuberculin test or post mortem visual inspection at slaughterhouse (mean (min–max) values)

Components	Observed[a]	Simulated expected
Purchase	9(2–14)	38,006 (224–101,042)
Slaughter	16(2–86)	870(26–4684)
Winter screening[b]: • Follow up of tracing on back of breakdown herds and import from non-officially bTB-free MS	390(65–498)	23,846(140–63,335)
• On farm delivery dairy farms	817(172–1486)	8987(52–23,816)

[a]FASFC 2010–2015.
[b]In the available data sources, it was not possible to clearly disentangle the reason of cattle and herds tested during winter screening.

TABLE 3 Scenarios simulation results of yearly alternative bovine tuberculosis (bTB) surveillance testing schemes (IFN-γ test, SIT, Ab-ELISA alone or in parallel with IFN-γ)): reactors at cattle level, component sensitivity, screening and confirmation testing price (mean (min–max) values)

	Screening with tuberculin skin test[a]	Screening with IFN-γ test	Screening with Ab-ELISA test	Screening with IFN-γ + Ab-ELISA test
TP	1(0–3)	1(0–3)	1(0–2)	1(0–3)
FN	0(0–1)	0(0–1)	1(0–2)	1(0–3)
FP	1434(5–7055)	303(28–1136)	1172(82–4667)	1448(132–5302)
TN	11,572(1679–27,232)	12,703(1856–28,692)	11,834(1746–26,486)	11,572(1679–27,232)
Component sensitivity	0.14(0.03–0.19)	0.11(0.02–0.18)	0.08(0.01–0.19)	0.14(0.03–0.19)
Price screening (€)	38,951(16,114–88,874)	240,753(36,622–625,026)	58,519(13,576–138,831)	292,794(43,719–713,194)
Price confirmation testing (€)	74,848(315–370,670)	15,841(1425–60,708)	61,141(4430–235,328)	75,530(7138–267,419)

Abbreviations: Ab-ELISA, antibody-enzyme linked immunosorbent assay; FN, false negatives; FP, false positives; IFN-γ, interferon gamma; TN, true negatives; TP, true positives.
[a]If tuberculin test is carried out in accordance with gold standard.

Ab-ELISA (€113,799 and €119,660), whereas cost for IFN-γ (€256,594) was substantially higher because of higher test costs. For a similar cost, the Ab-ELISA provided effective results in the same range as the SIT.

3.2 | Sensitivity analysis

The impacts of different simulated animal prevalence (1/1,000; 1/10,000; 1/100,000 infected) during purchase testing are shown in Figures 2. This graph indicates that regardless of the design prevalence (very low in disease freedom situations), most of the test results will be true negative (around 90%); the false negative rates remaining very low (around 0.01%). However, the expected rate of false positive results was high (around 10%).

Table 4 shows the impact of the use of different Ab-ELISA test sensitivity values. Component sensitivity remained constant and low (given the limited number of cattle herds tested compared with its corresponding herd population size) 0.09(0.00–0.19).

4 | DISCUSSION

The model developed for the purpose of this study has revealed itself to be an interesting tool to evaluate surveillance from different stakeholders' perspectives. Indeed, it has allowed the quantification of the system's performance in detecting and demonstrating freedom as well as its associated costs and potential risks (due to missed cases). This study highlighted the importance and interplay between sensitivity and specificity when evaluating surveillance performance in terms of costs and effectiveness. Computed simulated expected positive reactors (TP + FP) given the specificity of diagnostic testing procedures and tested cattle population, as well as prevalence, enabled a benchmark of expected results for the different surveillance components. Given expected prevalence of bTB in Belgium, most if not all positive reactors would be false positive and the simulated expected positive reactors corresponded to results published elsewhere (i.e. USDA publishes a minimum expected false positive results rate of 1% using SIT (USDA, 2017)). This current study simulated that a yearly minimum of 224 positive reactors are expected among the SIT tested cattle during

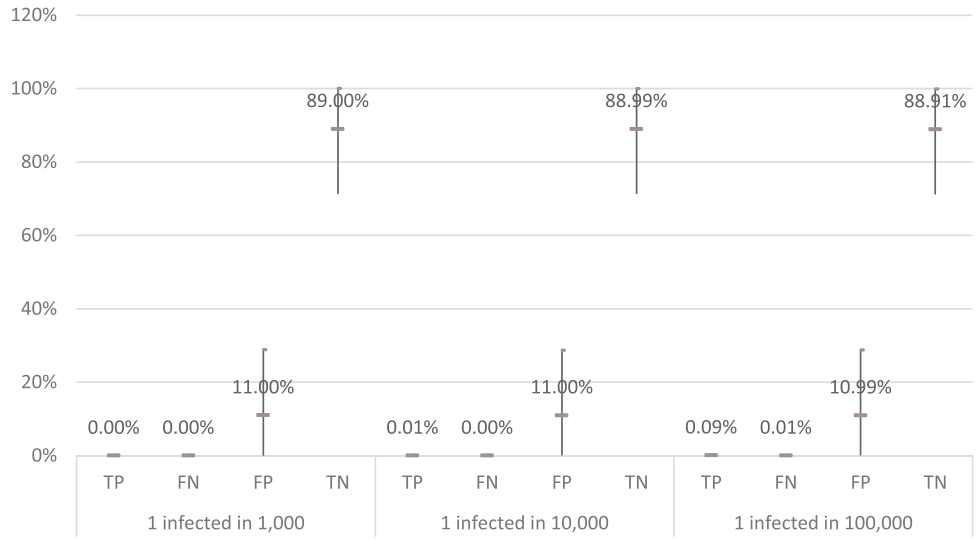

FIGURE 2 Simulated results (abbreviations: FN, false negatives; FP, false positives; TN, true negatives; TP, true positives) for varying prevalence during purchase testing with tuberculin skin test

TABLE 4 Impact of using different distributions and values of Ab-ELISA test sensitivity on bovine tuberculosis random cross-sectional surveillance: expected test results (component sensitivity, testing cost (screening + confirmation) (mean (min–max) values)

	Pert distribution (0.04,0.56,0.98)	Beta distribution (79,62)	Beta distribution (112,9)	Beta distribution (2,2)
TP	1(0–2)	1(0–2)	1(0–3)	1(0–2)
FN	1(0–2)	1(0–2)	0(0–0)	1(0–2)
FP	1172(82–4667)	1170(99–4292)	1172(98–4465)	1172(96–4713)
TN	11,834(1746–26,486)	11,836(1733–27,290)	11,834(1614–27,865)	11,834(1790–27,298)
Component sensitivity	0.08(0.00–0.19)	0.08(0.018–0.15)	0.15(0.04–0.19)	0.07(0.00–0.19)
Price screening (€)	58,519(13,576–138,831)	58,539(14,074–13,4450)	58,524(13,510–141,338)	58,515(13,292–144,526)
Price confirmation testing (€)	61,141(4430–235,328)	61,065(5352–243,202)	61,144(5151–239,445)	61,141(4814–238,972)

Abbreviations: FN, false negatives; FP, false positives; TN, true negatives; TP, true positives.

purchase, whereas in practice, over the last decade, between 2 (in 2011) and 14 (in 2013) only were reported yearly. Poor compliance with SIT testing procedure, because of a lack of disease awareness, of the fear of negative repercussions following notification, of logistical constraints (high number of cattle tested, containment of cattle not always appropriate), of biological variability or age (less likely to be infected and/or lower test sensitivity) could explain these discrepancies (Elbers et al., 2010; Humblet, Walravens, et al., 2011; Humblet, Moyen, et al., 2011; More et al., 2015; Schiller et al., 2010, 2011).

The current study revealed that SIT testing at purchase (in Belgian real-life field experience) showed a lower observed rate of detection than expected, more than a 1000-fold on average, and corroborated previous findings (Welby et al., 2012; Humblet et al., 2010). In this simulation exercise, minimum and maximum simulated expected values were purposely shown to reflect the range of all possible scenarios. This shows that in the very best-case scenario, 16-fold difference between the minimum expected number of positive reactors and the maximum observed and at purchase is found in the current Belgian field settings. If only the 95% confidence intervals were displayed, the discrepancy between the expected and observed number of reactors would only be greater. The estimated yearly costs of purchase testing, (€1,177,462; FASFC, personal communication, 2016), together with the overall indirect costs generated by compensation for slaughtered cattle in breakdown herds (€500,000/herd; FASFC, personal communication, 2016; Moniteur belge, 2003), appearing at a rather late stage of infection only, led to the search for a sustainable alternative.

For slaughterhouse visual inspection, the model simulated that a yearly number of suspect lesions between 26 and 4684 would be expected among slaughtered cattle. However, only 16 suspect gross lesions are spontaneously reported yearly. Considering historical data of early 2000, suspicious lesions submission rate was much higher (0.01%–0.08% of slaughtered cattle) and closer to expected results

simulated in the current study (C. Saegerman, personal communication, 2016). This has been an issue for TB surveillance throughout the world for both cattle and humans, with several interesting solutions such as, incentives, setting baseline targets of lesions to be detected, among others (Beith et al., 2009; EFSA, 2014; Kadota et al., 2021; Kaneene et al., 2006; More et al., 2015). In the United States, performance awards for detection of bTB-like lesions during slaughter have shown to have a significant impact on the detection of bTB cases (Kaneene et al., 2006). Another area of improvement in bovine tuberculosis surveillance is the rate of successful tracing back investigations of bovine tuberculosis-positive animals. In Belgium and Europe, the mandatory systematic registration and identification of animal origins, movement and status provide a wealth of data and information. Data quality, often considered as an asset, is critical to improve surveillance systems as value of information would be hampered by poor data quality (FAO, 2011; Stärk & Häsler, 2015). At the time of the study, in Belgium, while conventional laboratory samples (i.e. blood samples) data (i.e. animal ID, herd ID, test date, test motive and test result) are electronically, centralised and standardised recorded (similarly as for animal identification and movement data), lack of standardised and centralised SIT, SICT and slaughter samples could constitute a challenge and impact the rate of bTB notification. In addition, for the WS component, in the available data sources, it was not possible to clearly disentangle the reason of cattle and herds tested (i.e. five yearly follow up testing of cattle and herds identified following tracing-on and -back of bTB breakdown(s) and/or the three yearly follow up testing of cattle and herds due to introduction of cattle originating from a non-officially bTB-free MS). A centralised or integrated database with standardised data sets allowing for the merger of various data sources (i.e. between laboratory data and animal origins, movement and status) is critical to ensure rapid and efficient tracing on and back (Humphrey et al., 2014; Kaneene et al., 2006).

Diagnostics assays, such as Ab-ELISA and IFN-γ, gain increasing interest. These tests allow for individual testing as well as for general laboratory testing and would entail decreasing tester variability associated with pen-side tests such as the SIT (due to influences such as cattle calmness, the standard of the facilities, the interest and care of the veterinarian, etc.), thereby diminishing any pressure from owners on the veterinarian. With a single visit only, the overall financial cost could be potentially reduced. Over the last years, the initial low sensitivity and specificity of these assays were greatly improved (Bezos et al., 2014; Casal et al., 2017; Saegerman et al., 1995). Current diagnostic tests included in bTB control programmes focus mostly on cell mediated immune response, aiming at the prevention of an early stage spreading of the infection. However, as disease progresses, immunity slowly shifts from cell mediated to antibody response. Therefore, animals missed by current tests, which target cellular response (as implemented under current practices), would remain in the herd and could contribute to a spread of the disease, with significant economic losses as an outcome. Hence, using Ab-ELISA and IFN-γ (either alone or in parallel) in high-risk herds to increase the sensitivity of the surveillance scheme, to ensure the identification of latent infections and potentially silent bTB-spreading animals would be an interesting alternative. This approach would ensure breakdown management and rapid bTB eradication. The simulation exercise is performed in the current study, aiming at the assessment of impact, using these alternative testing schemes in specific surveillance components (i.e. monitor or tracing back contact herds and monitor cattle that originate from non-officially bTB MS). While the overall cost of parallel testing IFN-γ and Ab-ELISA is high in comparison with an SIT testing alone, the incremental effectiveness gained (given the current low prevalence setting in Belgium and poor performance of SIT in Belgian field setting) proved to be an interesting alternative. The IFN-γ test specificity values (0.98(0.95–0.99)) used to carry out simulation in this study were derived from existing literature at the time of the study. A recent meta-analysis corroborates these values, but it also highlights that caution should be taken given the variability that can be observed under certain conditions (Nuñez-Garcia et al., 2018). If the IFN-γ specificity were to be lower, because of the low prevalence and high number of cattle in the disease-free group, a 1% change in the number of non-diseased individuals correctly identified as negative, or the specificity, will have much bigger impact than a 1% change in the number of diseased individuals that correctly test positive, or the sensitivity. However, a pilot study evaluating the performance of the IFN-γ under field conditions in Belgium, proved comparable to the data in the literature (97%–98%), confirming thereby that assumptions used in other current modelling exercises are plausible in Belgium (FASFC, 2021). Nevertheless, further validation of these tests under field condition are warranted as suggested by Nuñez-Garcia et al. (2018).

To understand the impact of design prevalence on outputs from our simulation models, a sensitivity analysis was performed. The results show that if the true prevalence were to be higher than the current apparent prevalence, the number of potentially missed cases would remain in the same range. And that low disease prevalence situation, specificity of the test has a strong impact on surveillance system results. To measure impact from different Ab-ELISA diagnostic test sensitivity values on surveillance performance, additional simulations were carried out. Surprisingly, the impact was not significantly different. The large number of tested cattle and herds probably compensated for the varying values of sensitivity. The number of false negative test results, reflecting the probability of missing infected animals, remained substantially low regardless of the simulated diagnostic test sensitivity. As mentioned above, since the bTB prevalence is low in Belgium, given the bTB-free status of the country, a change in sensitivity will not have a big impact compared with a change in specificity. The beta probability distribution function is useful in modelling diagnostic test characteristics. The consistency in simulations results observed in the current study shows, however, that pert distribution function is a good approximation, when there is limited information about the shape of the distribution.

A prerequisite for securing public and animal health and welfare is cost-effective and sustainable surveillance systems. In addition, to ensure acceptability, surveillance systems should be tailored to answer to the needs and priorities of different animal health stakeholders. In Belgium, to ensure ownership and to involve farmers in a bottom-up approach for an ultimately sustainable decision-making process,

associating veterinarians, the agricultural food sector, regional and central laboratories, animal health control and policy making bodies, relevant authorities, paymasters is a common practice (Calba et al., 2016; Dehove et al., 2012; Hallet, 2003). The model developed in the current study enabled evidence-based decision and maintained a balance between cost and effectiveness, while providing assuredness in both a context of freedom and for disease detection. Simulation enabled us to quantify the impact of change in terms of cost and effectiveness and was a useful tool to facilitate the decision-making process regarding future tuberculosis surveillance in Belgium. It was agreed that testing at purchase, using the SIT test as currently performed in Belgium, was not cost-effective in detecting bTB cases in Belgium. Implementing a targeted use of the Ab-ELISA and IFN-γ tests was identified as an interesting alternative to mitigate the observed weak performance of the SIT in current Belgian real-life field experience (FASFC, 2020). Following this study, bTB surveillance was modified and Ab-ELISA and IFN-γ testing was implemented as the first-line screening test in all surveillance components (either sequentially or in parallel depending on which component), while purchase of cattle should comply with safe sanitary measures, the systematic testing with SIT of all purchased cattle was revised and centralised data epidemiological data base was set up (MB, 2021). The model framework developed in the current study proved to be an interesting tool for quantitative decision making regarding the (re)design of surveillance systems taking into account heterogeneity in local characteristics and different priorities and needs among stakeholders and in the light of evolving national and international regulations (EFSA, 2013, 2014; More et al., 2015; Welby et al., 2012).

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CONFLICT OF INTEREST

Sarah Welby is currently employed by GlaxoSmithKline Vaccines. The positions and opinions presented in this article reflect the work Sarah carried out during her employment at Sciensano, when the study was conducted and are not intended to represent the views or scientific works of GlaxoSmithKline. All other authors declare no conflict of interest.

ETHICS STATEMENT

The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to. No ethical approval was required as this is a research article with no original research data.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

Beith, A., Eichler, R., & Weil, D. (2009). Worldwide: Incentives for tuberculosis diagnosis and treatment. https://www.cgdev.org/sites/default/files/archive/doc/books/PBI/12_CGD_Eichler_Levine-Ch12.pdf

Bezos, J., Casal, C., Romero, B., Schroeder, B., Hardegger, R., Raeber, A. J., López, L., Rueda, P., & Domínguez, L. (2014). Current ante-mortem techniques for diagnosis of bovine tuberculosis. *Research in Veterinary Science*, *97*(Suppl), 44–52.

Calba, C., Goutard, F. L., Hoinville, L., Hendrikx, P., Lindberg, A., Saegerman, C., & Peyre, M. (2015). Surveillance systems evaluation: A systematic review of the existing approaches. *BMC Public Health*, *15*, 448.

Calba, C., Goutard, F. L., Vanholme, L., Antoine-Moussiaux, N., Hendrikx, P., & Saegerman, C. (2016). The added-value of using participatory approaches to assess the acceptability of surveillance systems: The case of bovine tuberculosis in Belgium. *Plos One*, *11*(7), e0159041. https://doi.org/10.1371/journal.pone.0159041.

Casal, C., Infantes, J. A., Risalde, M. A., Díez-Guerrier, A., Domínguez, M., Moreno, I., Romero, B., de Juan, L., Sáez, J. L., Juste, R., Gortázar, C., Domínguez, L., & Bezos, J. (2017). Antibody detection tests improve the sensitivity of tuberculosis diagnosis in cattle. *Research in Veterinary Science*, *112*, 214–221. https://doi.org/10.1016/j.rvsc.2017.05.012.

Conlan, A. J., McKinley, T. J., Karolemeas, K., Pollock, E. B., Goodchild, A. V., Mitchell, A. P., Birch, C. P., Clifton-Hadley, R. S., & Wood, J. L. (2012). Estimating the hidden burden of bovine tuberculosis in Great Britain. *Plos Computational Biology*, *8*(10), e1002730. https://doi.org/10.1371/journal.pcbi.1002730.

Dehove, A., Commault, J., Petitclerc, M., Teissier, M., & Macé, J. (2012). Economic analysis and costing of animal health: A literature review of methods and importance. *Revue Scientifique Et Technique (International Office of Epizootics)*, *31*(2), 605–617.

Drewe, J. A., Hoinville, L. J., Cook, A. J., Floyd, T., & Stärk, K. D. (2012). Evaluation of animal and public health surveillance systems: A systematic review. *Epidemiology and Infection*, *140*(4), 575–590.

Drewe, J. A., Häsler, B., Rushton, J., & Stärk, K. D. (2014). Assessing the expenditure distribution of animal health surveillance: The case of Great Britain. *Veterinary Record*, *174*(1), 16.

Downs, S. H., Parry, J. E., Upton, P. A., Broughan, J. M., Goodchild, A. V., Nuñez-Garcia, J., Greiner, M., Abernethy, D. A., Cameron, A. R., Cook, A. J., de la Rua-Domenech, R., Gunn, J., Pritchard, E., Rhodes, S., Rolfe, S., Sharp, M., Vordermeier, H. M., Watson, E., Welsh, M., … Clifton-Hadley, R. S. (2018). Methodology and preliminary results of a systematic literature review of ante-mortem and post-mortem diagnostic tests for bovine tuberculosis. *Preventive Veterinary Medicine*, *153*, 117–126. https://doi.org/10.1016/j.prevetmed.2017.11.004.

Downs, S. H., More, S. J., Goodchild, A. V., Whelan, A. O., Abernethy, D. A., Broughan, J. M., Cameron, A., Cook, A. J., Ricardo de la Rua-Domenech, R., Greiner, M., Gunn, J., Nuñez-Garcia, J., Rhodes, S., Rolfe, S. B., Sharp, M., Upton, P., Watson, E., Welsh, M., Woolliams, J. A., … Parry, J. E. (2018). Evaluation of the methodological quality of studies of the performance of diagnostic tests for bovine tuberculosis using QUADAS. *Preventive Veterinary Medicine*, *153*, 108–116. https://doi.org/10.1016/j.prevetmed.2017.03.006.

Elbers, A. R. W., Gorgievski-Duijvesteijn, M. J., van der Velden, P. G., Loeffen, W. L. A., & Zarafshani, K. (2010). A socio-phychological investigation into limitations and incentives concerning reporting a clinically suspect situation aimed at improving early detection of classical swine fever outbreaks. *Preventive Veterinary Medicine*, *142*, 108–118.

European Food Safety Agency (EFSA) (2013). Modelling the impact of a change in meat inspection sensitivity on the surveillance of bovine tuberculosis at country level. http://www.efsa.europa.eu/en/supporting/pub/450e.htm.

European Food Safety Agency (EFSA) (2014). Statement of a conceptual framework for bovine tuberculosis. http://www.efsa.europa.eu/en/efsajournal/pub/3711.htm.

European Food Safety Agency (EFSA) (2018). The European Union summary report on trends and sources of zoonoses, zoonotic agents and food-borne outbreaks in 2017. *EFSA Journal*, *16*(12), e05500.

European Commission (EC) (1964). Council Directive of 26 June 1964 on animal health problems affecting intra-Community trade in bovine animals and swine 64/432/EEC. *Official Journal*, *121*, 1977.

European Commission (EC) (2003). Commission Decision of 23 June 2003 establishing the official tuberculosis, brucellosis, and enzootic bovine leucosis free status of certain Member States and regions of Member States as regards bovine herds 2003/467/EC. *Official Journal*, *156*, 74.

Food and Agriculture Organisation (FAO) (2011). Challenges of animal health information systems and surveillance for animal diseases and zoonoses. http://www.fao.org/docrep/014/i2415e/i2415e00.htm.

Federal Agency for the Safety of the Food Chain (FASFC) (2016). Scientific committee opinion 2015/11: Evaluation of the Belgian bovine tuberculosis control program. http://www.afsca.be/scientificcommittee/opinions/2016/documents/Opinion12-2016_Tuberculose.pdf.

Federal Agency for the Safety of the Food Chain (FASFC) (2020). Santé animale: Tuberculose bovine. http://www.favv-afsca.be/santeanimale/tuberculose/

Federal Agency for the Safety of the Food Chain (FASFC) (2021). Santé animale: Tuberculose bovine. https://www.favv-afsca.be/santeanimale/tuberculose/_documents/3NRLSciensano.pdf

Garcia-Saenz, A., Napp, S., Lopez, S., Casal, J., & Allepuz, A. (2015). Estimation of the individual slaughterhouse surveillance sensitivity for bovine tuberculosis in Catalonia (North-Eastern Spain). *Preventive Veterinary Medicine*, *121*(3–4), 332–337. https://doi.org/10.1016/j.prevetmed.2015.08.008.

Guta, S., Casal, J., Napp, S., Saez, J. L., Garcia-Saenz, A., Perez de Val, B., Romero, B., Alvarez, J., & Allepuz, A. (2014). Epidemiological Investigation of bovine tuberculosis herd breakdowns in Spain 2009/2011. *Plos One*, *9*(8), e104383. https://doi.org/10.1371/journal.pone.0104383.

Hallet, L. (2003). Collaboration between official veterinarians, private veterinarians and livestock producer organisations. *Revue Scientifique et Technique*, *22*(2), 523–532

Humblet, M. F., Boschiroli, M. L., & Saegerman, C. (2009). Classification of worldwide bovine tuberculosis risk factors in cattle: A stratified approach. *Veterinary Research*, *40*(5): 50.

Humblet, M. F., Gilbert, M., Govaerts, M., Fauville-Dufaux, M., Walravens, K., & Saegerman, C. (2010). New assessment of bovine tuberculosis risk factors in Belgium based on nationwide molecular epidemiology. *Journal of Clinical Microbiology*, *48*(8), 2802–2808.

Humblet, M. F., Walravens, K., Salandre, O., Boschiroli, M. L., Gilbert, M., Berkvens, D., Fauville-Dufaux, M., Godfroid, J., Dufey, J., Raskin, A., Vanholme, L., & Saegerman, C. (2011) Monitoring of the intra-dermal tuberculosis skin test performed by Belgian field practitioners. *Research in Veterinary Science*, *91*, 199–207.

Humblet, M. F., Moyen, J. L., Bardoux, P., Boschiroli, M. L., & Saegerman, C. (2011). The importance of awareness for veterinarians involved in cattle tuberculosis skin testing. *Transboundary and Emerging Diseases*, *58*(6), 531–536.

Humphrey, H. M., Orloski, K. A., & Olea-Popelka, F. J. (2014). Bovine tuberculosis slaughter surveillance in the United States 2001–2010: Assessment of its traceback investigation function. *BMC Veterinary Research*, *10*, 182. https://doi.org/10.1186/s12917-014-0182-y.

Kadota, J. L., Nabwire, S., Nalugwa, T., White, J. S., Cattamanchi, A., Katamba, A., & Shete, P. B. (2021). Patient perspectives and willingness to accept incentives for tuberculosis diagnostic evaluation in Uganda. *Value in Health Regional Issues*, *25*, 48–56. https://doi.org/10.1016/j.vhri.2020.12.005.

Kaneene, J. B., Miller, R., & Meyer, R. M. (2006). Abattoir surveillance: The U.S. experience. *Veterinary Microbiology*, *112*(2–4), 273–282. https://doi.org/10.1016/j.vetmic.2005.11.018. PMID: 16326037.

King, H. C., Murphy, A., James, P., Travis, E., Porter, D., Hung, Y. J., Sawyer, J., Cork, J., Delahay, R. J., Gaze, W., Courtenay, O., & Wellington, E. M. (2015). The variability and seasonality of the environmental reservoir of Mycobacterium bovis shed by wild European badgers. *Scientific Reports*, *6*(5), 12318. https://doi.org/10.1038/srep12318.

Martin, P. A., Cameron, A. R., & Greiner, M. (2007). Demonstrating freedom from disease using multiple complex data sources 1: A new methodology based on scenario trees. *Preventive Veterinary Medicine*, *79*(2–4), 71–97.

Moniteur Belge (MB) (2003). Arrêté royal du 17 Octobre 2002 relatif à la lutte contre la tuberculose bovine. *Moniteur Belge*, *2003022000*, 12448.

Moniteur Belge (MB) (2021). Arrêté royal relatif à la lutte contre la tuberculose bovine. http://environnement.wallonie.be/legis/agriculture/federal/federal029.htm

More, S. J., Radunz, B., & Glanville, R. J. (2015). Lessons learned during the successful eradication of bovine tuberculosis from Australia. *Veterinary Record*, *177*(9), 224–232.

Nuñez-Garcia, J., Downs, S. H., Parry, J. E., Abernethy, D. A., Broughan, J. M., Cameron, A. R., Cook, A. J., de la Rua-Domenech, R., Goodchild, A. V., Gunn, J., More, S. J., Rhodes, S., Rolfe, S., Sharp, M., Upton, P. A., Vordermeier, H. M., Watson, E., Welsh, M., Whelan, A. O., Woolliams, J. A., Clifton-Hadley, R. S., & Greiner, M. (2018). Meta-analyses of the sensitivity and specificity of ante-mortem and post-mortem diagnostic tests for bovine tuberculosis in the UK and Ireland. *Preventive Veterinary Medicine*, *153*, 94–107. https://doi.org/10.1016/j.prevetmed.2017.02.017. PMID: 28347519.

Palisson, A., Courcoul, A., & Durand, B. (2016). Role of cattle movements in bovine tuberculosis spread in France between 2005 and 2014. *Plos One*, *11*(3), e0152578.

Quadri, N. S., Brihn, A., Shah, J. A., & Kirsch, J D. (2021). Bovine tuberculosis: A re-emerging zoonotic infection. *Journal of Agromedicine*, *26*, 334–339. https://doi.org/10.1080/1059924X.2020.1771497. PMID: 32478614.

Saegerman, C., Delville, J., De Waele, L., & Gilson, D. (1995). Serological and cutaneous testing of bovine tuberculosis with the A60 antigen complex from Mycobacterium bovis, strain Calmette-Guérin. *Preventive Veterinary Medicine*, *23*, 239–248.

Schiller, I., Oesch, B., Vordermeier, H. M., Palmer, M. V., Harris, B. N., Orloski, K. A., Buddle, B. M., Thacker, T. C., Lyashchenko, K. P., & Waters, W. R. (2010). Bovine tuberculosis: A review of current and emerging diagnostic techniques in view of their relevance for disease control and eradication. *Transboundary and Emerging Diseases*, *57*(4), 205–220.

Schiller, I., Waters, W. R., Vordermeier, H. M., Jemmi, T., Welsh, M., Keck, N., Whelan, A., Gormley, E., Boschiroli, M. L., Moyen, J. L., Vela, C., Cagiola, M., Buddle, B. M., Palmer, M., Thacker, T., & Oesch, B. (2011). Bovine tuberculosis in Europe from the perspective of an officially tuberculosis free country: Trade, surveillance and diagnostics. *Veterinary Microbiology*, *151*, 153–159.

Stärk, K. D., & Häsler, B. (2015). The value of information: Current challenges in surveillance implementation. *Preventive Veterinary Medicine*, *122*(1–2), 229–234. https://doi.org/10.1016/j.prevetmed.2015.05.002.

United States Department of Agriculture (USDA) (2017). Bovine Tuberculosis: Caudal Fold Testing and Reporting. https://aglearn.usda.gov/customcontent/APHIS/APHIS-VS-BovineTuberculosis-01/scopage_dir/cftreport/cftreport.html.

Welby, S., Govaerts, M., Vanholme, L., Hooyberghs, J., Mennens, K., Maes, L., & Van Der Stede, Y., (2012). Bovine tuberculosis surveillance alternatives in Belgium. *Preventive Veterinary Medicine*, *106*(2), 152–161.

VISAVET (2019). Bovine tuberculosis eradication in Europe. https://www.visavet.es/bovinetuberculosis/bovine-tb/eradication.php

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